

Extragalactic X-ray Surveys: AGN physics and evolution

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We review the most important findings on AGN physics and cosmological evolution as obtained by extragalactic X-ray surveys and associated multiwavelength observations. We briefly discuss the perspectives for future enterprises and in particular the scientific case for an extremely deep (2–3 Ms) XMM survey

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1 Introduction

Since their launch in 1999, both XMM-Newton and Chandra have performed a large (> 30) number of surveys covering a wide fraction of the area vs. depth plane (see fig 1 in Brandt & Hasinger 2005). Thanks to vigorous programs of multiwavelength follow-up observations which, since a few years, have become customary, our understanding of AGN evolution has received a major boost. The high level of completeness in redshift determination for a large number of X-ray selected AGN (up to a few thousands) has made possible a robust determination of the luminosity function and evolution of unobscured and mildly obscured AGN (Ueda et al. 2003; Hasinger et al. 2005; La Franca et al. 2005), which turned out to be luminosity dependent: the space density of bright QSO ($L_X > 10^{44}$ erg s⁻¹) peaks at $z \sim 2-3$, to be compared with the $z \sim 0.7-1$ peak of lower luminosity Seyfert galaxies.

The fraction of obscured AGN is also strongly dependent from the X-ray luminosity (Ueda et al. 2003; La Franca et al. 2005). Even though the shape and the normalization of the function describing the obscured fraction vs. luminosity is still matter of debate, it is clear that absorption is much more common at low X-ray luminosities. Such a trend has been observed also in the optical (Simpson 2005) and in the near infrared (Maiolino et al. 2007) and may be linked to the AGN radiative power which is able to ionize and expel gas and dust from the nuclear regions. More debated is the claim of an increase of the obscured fraction towards high redshifts. First suggested by La Franca et al. (2005), it has been confirmed by Treister & Urry (2006), while it is not required in the models discussed by Ueda et al. (2003) and Gilli et al. (2007).

A redshift dependence of the obscuring fraction would be naturally explained in the current framework of AGN

formation and evolution (see, for example, Hopkins et al. 2006): the anti-hierarchical behaviour observed in AGN evolution (similar to that observed in normal galaxies), along with several other evidences, suggests that supermassive black holes (SMBH) and their host galaxies co-evolve and that their formation and evolution are most likely different aspects of the same astrophysical problem. At early times large quantities of cold gas were available to efficiently feed and obscure the growing black holes. Later on, the ionizing nuclear flux is able to "clean" its environment appearing as an unobscured QSO. However, the picture sketched above is likely to be much more complicated, depending on many other parameters (such as the BH mass, the Eddington ratio, the QSO duty cycle) and may not necessarily result in an increasing fraction of obscuration towards high redshifts.

It should also be remarked that sensitive X-ray observations are highly efficient to unveil weak and/or elusive accreting black holes which would be missed, or not classified as such, by surveys at longer wavelengths. Among them XBONG (Comastri et al. 2002), sources with high X-ray to optical flux ratio (Fiore et al. 2003), Extremely Red Objects (Brusa et al. 2005), Sub Millimeter Galaxies (Alexander et al. 2005). Although they are probably not representative of the sources of the X-ray background their study has allowed us to better understand the physics of accreting black holes.

Finally, the coverage of several Chandra and XMM fields has allowed to uncover several redshifts spikes in the distribution of X-ray sources (Gilli et al. 2005) and demonstrated that AGN may be used as reliable tracers of the large scales structures. The underlying large scale structure may play an important role in triggering AGN activity. According to the analysis of a sample of X-ray selected AGN in the AEGIS survey, Georgakakis et al. (2006) suggest that $z \sim 1$ AGN are more frequent in dense environments.

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2 Open Questions

The most important achievements, briefly outlined above, were obtained combining data from both deep and large area surveys. The former were conceived to reach extremely faint fluxes at the expenses of a reduced sky coverage, while for the latter the search of a trade-off between area and exposure time is the main driver. Both the approaches have their own scientific goals which cannot be directly compared, but rather considered as a necessary synergy. The deepest surveys in the *Chandra* Deep Fields North and South (CDF) have reached extremely faint fluxes over a relatively small (~ 400 arcmin² each) portion of the sky and represent an unique resource for the study of the faint end of the luminosity function and the discovery of distant and obscured AGN. The search for most luminous quasars and the study of the clustering of the AGN population is uniquely pursued by large area surveys. At present the most relevant projects in terms of area, X-ray flux and multiwavelength follow-up programs are the XMM-COSMOS 2 sq. degree survey (Hasinger et al. 2007, Cappelluti et al. 2007), the *Chandra*-AEGIS survey (Nandra et al. 2005) and the Extended CDFS (Lehmer et al. 2005).

New results always bring new questions. An exhaustive review of open problems is beyond the purposes of the present paper and we highlight what we consider the most pressing questions and which of them could be answered by future XMM-*Newton* surveys.

As far as SMBH are most directly concerned, attention is now focused on a few key questions:

- How is star formation and gas accretion linked ? How strong is the relative feedback ? What is the role of the environment in triggering AGN activity ?
- How many highly obscured AGN are still missing, how much do they contribute to the accretion history and SMBH mass budget in the Universe ?
- How strong is the dependence of obscuration upon luminosity and redshift ? Are emission $K\alpha$ lines common also at high redshift ?
- What is the space density of high redshift (> 3) quasars ? How many of them are obscured ?

Some of these topics are being addressed with the available multiwavelength data.

2.1 “Missing” AGN

The X-ray background (XRB) below 5–6 keV (Worsley et al. 2005), has been almost completely resolved into single sources, the large majority of them being obscured by substantial amounts of gas (up to 10^{24} cm⁻²; i.e. in the Compton thin regime), thus nicely confirming the predictions of AGN synthesis models. The *unresolved* XRB fraction, which provides an integral constraint to the number of “missing” AGN, increases with energy and is close to 100% at the 30 keV peak. A good fit is obtained if a population of heavily obscured Compton Thick (CT; $N_H > 10^{24}$ cm⁻²)

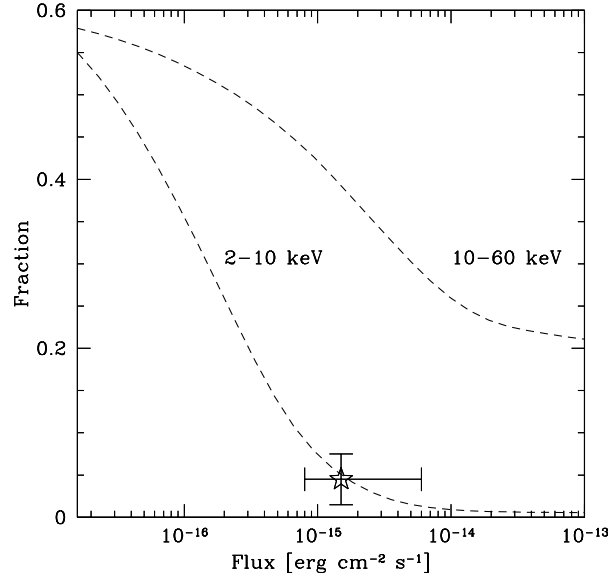


Fig. 1 The predicted fraction of CT AGN (Gilli et al. 2007) as a function of the X-ray flux in the 2–10 keV band along with the estimate of Tozzi et al. (2006). The model predicted fraction in the 10–60 keV band is also reported.

AGN whose space density is of the same order of that of Compton thin is added. Such an estimate is model dependent and probably subject to large uncertainties however, while abundant in the local Universe, only a handful of CT AGN are known at cosmological distances (see Comastri 2004 for a review). Either CT AGN are numerous also at high z and the bulk of population is still undetected, or they represent a “local” phenomenon possibly associated with a “final” phase in the evolution of nuclear obscuration. In the latter hypothesis the 30 keV peak of the XRB would originate in different, yet unknown, sources. According to synthesis models the fraction of CT AGN is expected to steeply increase just beyond the present limits (Fig. 1) and indeed the deepest search for CT AGN in the X-ray band (Tozzi et al. 2006) uncovered a number of candidates which is fairly consistent with the model predictions, supporting the hypothesis that CT AGN are too faint to be directly detected in the X-ray band.

Alternative techniques, based on the selection via infrared and radio data, seem promising (i.e. Martinez Sanz et al. 2005). Indeed Fiore et al. (2007) and Daddi et al. (2007) were able to recover the “missing” obscured CT AGN population making use of $24\mu\text{m}$ *Spitzer* observations and deep near-infrared and optical data. Stacking of the X-ray counts of CT candidates selected on the basis of an infrared excess and individually undetected in the CDF Ms exposures, revealed a strong signal in the hard (~ 4 –8 keV) band which imply, at their average redshift ($z \sim 2$), absorption column densities in the CT regime. The census of CT and obscured AGN population bears important consequences for the study of the assembly and evolution of SMBH.

For example the mass function of Compton thin AGN, estimated from the luminosity function of X-ray selected AGN, falls short by a factor 2 from that of "relic" SMBH in local bulges (Marconi et al. 2004). The candidate CT AGN population selected in the infrared would have the right size to reconcile the two SMBH mass function estimates. It has also been suggested that the absorption by CT matter of high energy photons may be able to efficiently heat the surrounding material through Compton scattering (Daddi et al. 2007). CT sources may thus play a key role in the AGN feedback eventually leading to the quenching of star formation.

2.2 High-redshift Quasars

The space density and evolution of high redshift QSO is still an open issue. In the optical band, mainly thanks to the SDSS, their luminosity function is relatively well known up to $z \sim 6$. Although the highest redshift QSO are known to be X-ray emitters (Vignali et al. 2003) the lack of sensitive and wide enough surveys with a fairly homogenous and complete coverage has not allowed to obtain reliable estimates of high redshift X-ray selected QSO. The XMM-COSMOS survey is starting to fill this gap. So far seven spectroscopically confirmed QSO at $z > 3$ were found above a flux of 2×10^{-15} cgs (where the sky coverage is flat over the entire 2 sq degs area). By fully exploiting the multicolor optical and near infrared diagrams several candidate $z > 3$ QSO are found at the same limiting flux, bringing the total number of candidate in the COSMOS field to ~ 40 (Brusa et al. in preparation). The upper and lower limits of the $z > 3$ QSO counts are reported in Fig. 2, along with the number counts of the overall X-ray source population from a compilation of different surveys (Cappelluti et al. 2007). The two magenta lines show the contribution of $z > 3$ QSO predicted by XRB synthesis models (Gilli, Comastri & Hasinger 2007) upon two different assumptions on their high redshift evolution: an exponential decline at $z > 3$ as parameterized by Schmidt et al. (1995) or a constant space density. Although the actual number of $z > 3$ QSO in the COSMOS field suffers from large uncertainties, the present data would suggest that a constant space density at high redshift is ruled out.

3 Perspectives

In order to properly address the key questions a better sensitivity, over a large sky area as well as an extended energy range than obtained to date, are required. While in principle one would need all of them at once, in practice this is impossible. An ultradeep (2–3 Ms) hard X-ray survey with XMM-Newton would allow the scientific community to address with an unprecedented accuracy several of the "key" questions outlined above and in particular those concerning the most obscured "missing" AGN and the X-ray

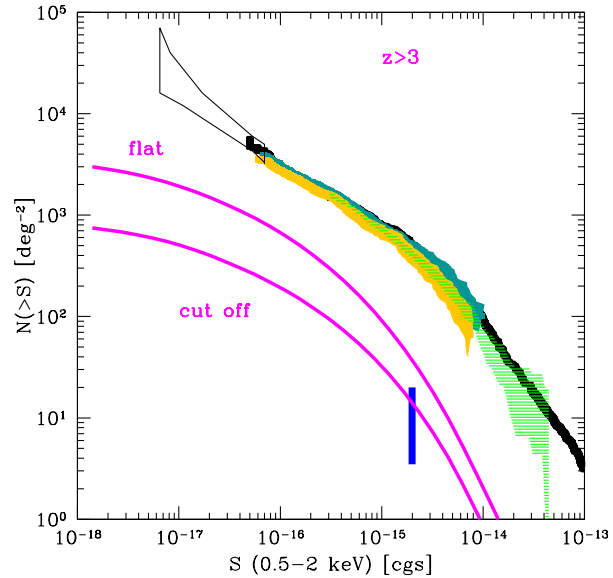


Fig. 2 The observed space density of $z > 3$ quasars in the COSMOS field (blue vertical line) compared with the predicted number counts (Gilli et al. 2007) under two different hypotheses (see text)

spectral properties (absorption, emission lines, etc) of distant sources. The large collecting area and hard X-ray sensitivity of the imaging detectors onboard XMM have not yet been pushed to their limits (the deepest XMM survey in the Lockman Hole reached an exposure time of ~ 700 ks). According to our calculations (see also Carrera et al. this volume) the EPIC camera would not be confusion limited down to fluxes of the order of $3 - 5 \times 10^{-16}$ cgs in the 5–10 keV band corresponding to a factor 3–4 deeper than the present limits (Fig. 3).

The model predicted logN–logS of CT AGN, in the 5–10 keV energy range, has a steep slope down to faint fluxes and thus a deeper exposure would allow to detect several new candidates, presumably at moderate to high redshifts, responsible for the unresolved XRB. Given that the Gilli et al. (2007) model reproduce the XRB level measured by HEAO1 (fig. 4), the predicted counts should be considered as a lower limit. The very shape and normalization of the XRB spectrum in the ≈ 5 –15 keV band is, at present, quite uncertain. On the one hand, recent BeppoSAX (Frontera et al. 2007); INTEGRAL (Churazov et al. 2007) and Swift (Ajello et al. in preparation) observations have unambiguously demonstrated that the XRB intensity above 15 keV is close to that measured by HEAO1 (fig. 4). On the other hand, according to a detailed analysis of deep *Chandra* field (Hickox & Markevitch 2006) the XRB level, below about 5 keV, is some 30% higher than the extrapolation of higher energy data. Given that the summed contribution of faint *Chandra* sources in the 1–8 keV band is already exceeding, at the face value, the HEAO1 level, it may well be possible that a much larger fraction than that quoted by Worsley et

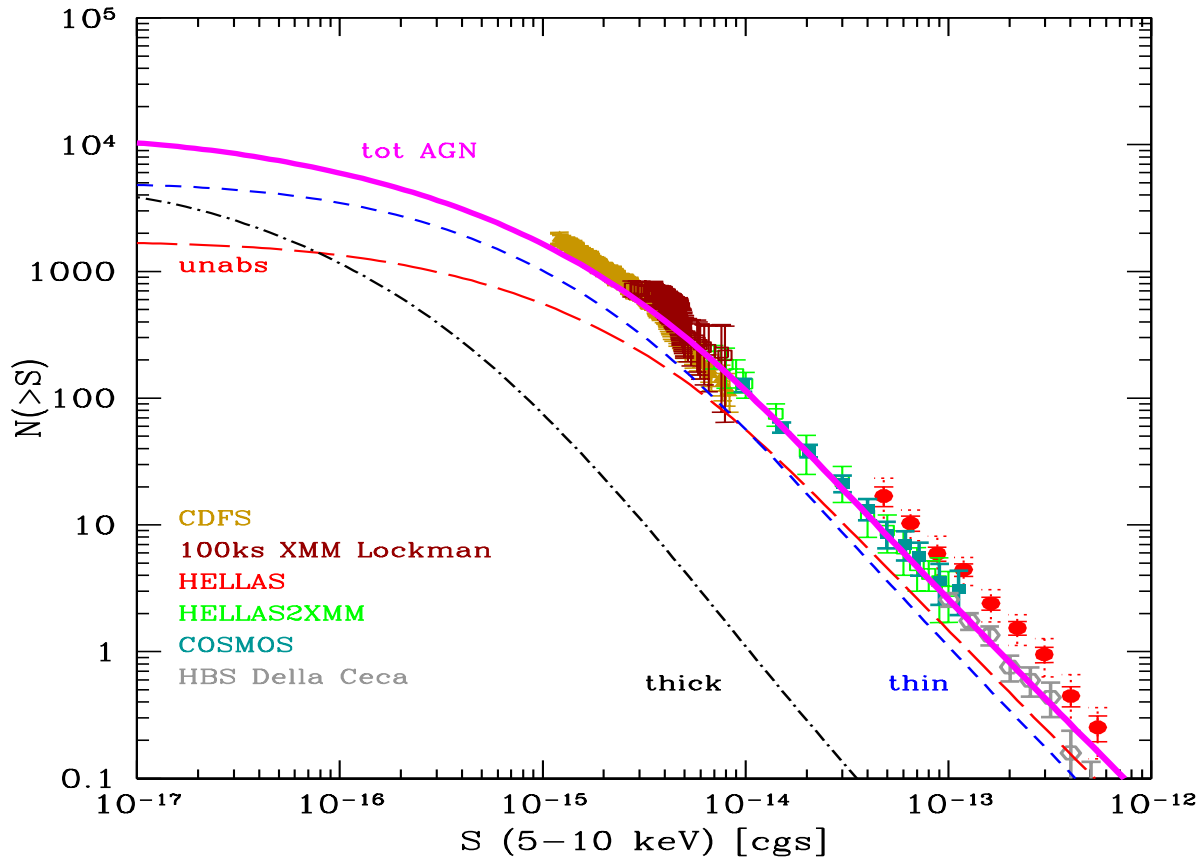


Fig. 3 The 5–10 keV counts, from a compilation of several surveys as labeled, compared with the Gilli et al 2007 model predictions for unobscured (red line), Compton thin (blue line), Compton Thick (black line), and total AGN (magenta line)

al. (2005) has been already resolved. Alternatively, a sizable population of extremely hard sources, appearing only above 5–6 keV, and not accounted for in the XRB synthesis model, are providing a significant contribution.

Interesting enough fully, 4π , covered AGN with a negligible fraction of scattered flux in the soft X-rays may provide a relevant contribution only above 5 keV or even more depending from their redshift and column density. A few examples of these sources in the local Universe were recently discovered with Suzaku (Ueda et al. 2007; Comastri et al. 2007). Should a population of heavily obscured, fully covered AGN be abundant at moderate to high redshifts they might be discovered only by sensitive surveys above 5 keV.

A deep XMM survey would allow to collect good quality X-ray spectra for a large number of sources. The obvious advantages of an improved spectral analysis concern a better determination of the absorption column densities especially at high redshifts where the determinations based on the Hardness Ratios suffer of the largest uncertainties.

The studies based on the stacking of X-ray detected sources would also benefit from an improved counting statistic. Such a technique has been widely adopted for different purposes. Among them, the study of the intensity and profile of iron K line in the average spectrum of faint AGN.

Convincing evidence for the presence of iron emission up to high ($z \sim 2-3$) redshifts has been presented by Brusa et al. (2005), while Streblyanska et al. (2005) reported the discovery of a broad line with an extended red wing in the average spectra of both Type 1 and Type 2 AGN. The line profile brings unique information on the SMBH spin and is the signature that General Relativistic effects are at work in the innermost regions of AGN.

An ultra-deep X-ray survey is also well suited to search for high redshift AGN. As shown in Fig. 2, the differences in the counts for a model with and without a cut-off in the evolution at high redshift increase towards faint fluxes. Moreover, the search for accreting SMBH among various classes of objects selected on the basis of longer wavelength properties (see § 2.1) can be exploited in more detail. It is worth mentioning that the selection on the basis of an extreme infrared to optical color seems quite promising to pick up the first ($z > 6$) QSO (Koekemoer et al. 2004).

The merit of an ultra-deep XMM survey should be judged in the context of multiwavelength deep surveys and its scientific return would be maximized if it is carried out in the best studied fields. The excellent coverage of the Chandra Deep Field South with both present and future (i.e. ALMA and SKA) facilities, along with the already planned ad-

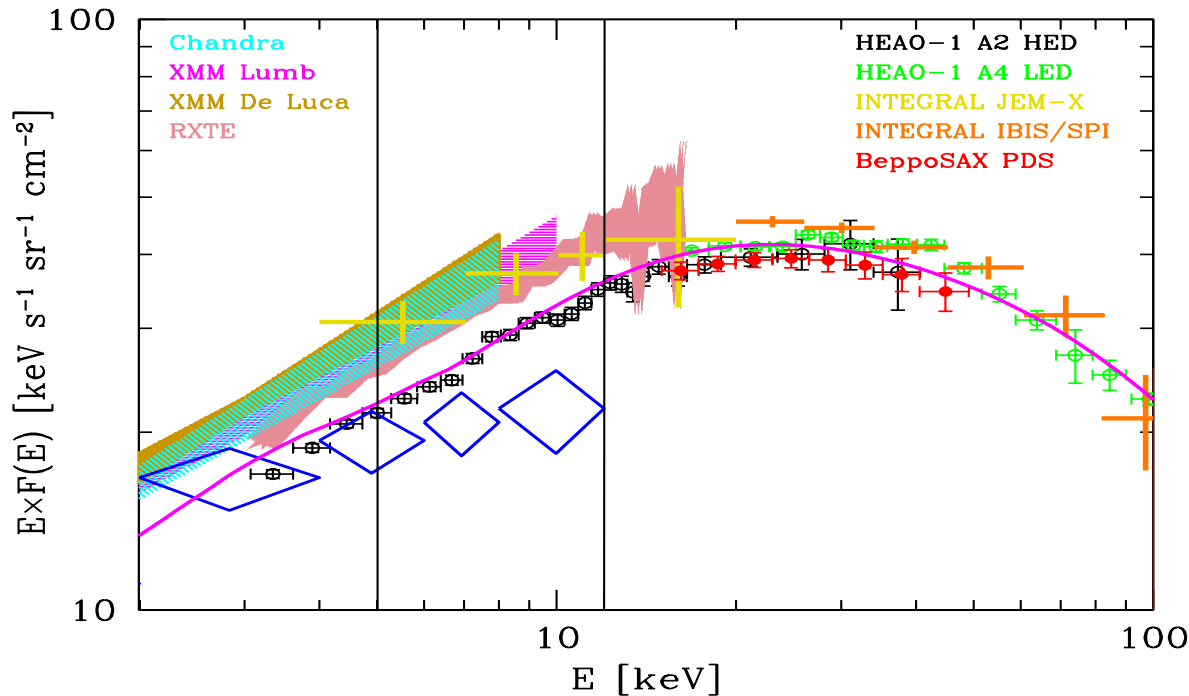


Fig. 4 A selection of XRB measurements, including the resolved fraction in deep fields (blue squares) and the best fit (magenta line) AGN synthesis model of Gilli et al. (2007). The vertical lines mark the 5–12 keV energy range

ditional 1 Ms of DDT *Chandra* data, are making the CDFS a legacy field for the years to come. The so-called co-evolution of AGN and host galaxies and their mutual feedback represents one of the most important achievements in the field of observational cosmology. It is by now clear that further advances can be obtained only by joining the efforts of people working in apparently different fields and at different wavelengths (crudely: optical near-IR for the galaxy evolution, X-ray surveys for AGN). Deep XMM observations will, at the same time, benefit and enhance the return of the many common scientific goals.

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